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A TECHNIQUE FOR DYNAMICALLY CALIBRATING PRESSURE
TRANSDUCERS AT CRYOGENIC TEMPERATURES

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CALIBRATING PRESSURE TRANSDUCERS AT
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SUMMARY

A technique has been developed for the calibration of dynamic pressure transducers at cryogenic temperatures. The calibration system utilizes an 8.9 Newton peak thrust shaker which oscillates a helium-filled bellows to generate a sinusoidal dynamic pressure to calibrate transducers immersed in a cryogenic environment. The system has a dynamic pressure measurement uncertainty of approximately 11% and is capable of producing peak-to-peak dynamic pressure amplitudes of 1.4 kPa over a frequency range of 40 to 100 hertz and a temperature range of 100 to 300 K. It provides an unprecedented capability of both static and dynamic calibration of pressure transducers from ambient to cryogenic temperature.

INTRODUCTION

The development of the National Transonic Facility, a cryogenic wind tunnel for high Reynolds' number aerodynamic research, has introduced several new measurement areas. One of these areas is dynamic pressure measurement at cryogenic temperature. Cryogenic pressure transducers are currently available commercially in a limited number of designs, however the dynamic calibration of cryogenic pressure transducers is not provided by the manufacturers. A literature search has revealed no information on the successful development of a dynamic calibration technique for cryogenic pressure transducers. Pressure transducers are currently calibrated statically using a step-function method at both ambient and cryogenic temperatures, and dynamically using quick opening valve/shock tube techniques at ambient temperatures. This paper describes the design, development, and testing of a new cryogenic, dynamic calibration system.

SYMBOLS

- A = Cross-sectional area of bellows, cm^2
- P = Static test pressure inside bellows, kPa
- V = Volume of transducer-bellows assembly in unloaded position, cm^3
- T = Temperature, K
- $P_{\text{p-p}}$ = Peak-to-peak dynamic pressure, kPa
- L = Displacement of bellows drive rod, cm

THEORY

This calibration system was based on the reciprocation of a sealed metal bellows producing a sinusoidal pressure with a calculable peak-to-peak value. Given the linear bellows displacement (L), the volume (V) of the transducer-bellows assembly, the bellows cross-sectional area (A), and the initial internal static pressure (P), peak-to-peak dynamic pressure (P_{p-p}) can be calculated. Two expressions were used to calculate the value, PV , according to the ideal gas law. One accounts for the compression (1a.) of the bellows and the second accounts for the expansion (1b.) during its sinusoidal reciprocation.

$$(PV)_c = (P + \Delta P_1) (V - \Delta V_1) \quad (1a.)$$

$$(PV)_e = (P - \Delta P_2) (V + \Delta V_2) \quad (1b.)$$

Solving for the change in pressure due to compression (2a.) and expansion (2b.);

$$\Delta P_1 = (PV)_c / (V - \Delta V_1) - P \quad (2a.)$$

$$\text{and} \quad \Delta P_2 = P - (PV)_e / (V + \Delta V_2) \quad (2b.)$$

Equation (3) represents the peak-to-peak sinusoidal pressure (P_{p-p}) as a total of pressure change produced by compression and expansion.

$$P_{p-p} = \Delta P_1 + \Delta P_2 = (PV)_c / (V - \Delta V_1) - (PV)_e / (V + \Delta V_2) \quad (3)$$

Substituting ($AL/2$) for the change in volume due to expansion and to compression:

$$P_{p-p} = (PV)_c / (V - AL/2) - (PV)_e / (V + AL/2) \quad (4)$$

Equation (4) is simplified to obtain equation (5), the expression for peak-to-peak sinusoidal dynamic pressure:

$$P_{p-p} = 4 PVAL / (4V^2 - A^2 L^2) \quad (5)$$

APPARATUS

The primary element of the calibration system apparatus (figure 1) is a reciprocating bellows which develops the time varying pressure waveform applied to the transducers. Calibration is performed by comparing the response of the transducers to the time varying pressure calculated from the measured linear motion of the bellows. The bellows and transducer manifold assembly are immersed in the cryogenic environment to minimize thermal gradients in the controllable cryogenic temperature. The bellows is reciprocated using a small vibration generator mounted outside the cryogenic chamber and linked to the bellows by a steel-drive rod (figure 2). Dynamic pressure amplitude is controlled by adjusting the static helium pressure in the bellows and by controlling the amplitude of vibration.

The bellows used in the test apparatus is a 1.8-cm long, 0.38 cm i.d. nickel bellows with a spring rate of 10.3 N/cm and a maximum stroke of ± 0.4 cm. It is driven by an 8.9 Newton peak-thrust vibration generator having a stroke of ± 0.32 cm. The generator is linked to the bellows by a steel-drive rod 16 cm long and 0.4 cm in diameter. One end of the bellows is fixed while the other is free to oscillate with the motion of the drive rod. Test and reference transducers are connected symmetrically to an adapter on the fixed end of the bellows. The volume of the bellows and adapter assembly is 0.66 cm^3 . A 0.135 cm drive rod stroke, with a static pressure of 34.5 kPa (5 psid) inside the bellows, will produce a volume change of 0.026 cm^3 and a peak-to-peak dynamic pressure of approximately 1.4 kPa (0.2 psi).

The vibration generator, helium pressure control valves, and instrumentation are located outside the environmental chamber. Linear displacement of the bellows is measured using a proximity probe mounted on the drive rod. Displacement is measured by mounting a thin strip of steel on the bellows drive rod with the proximity probe mounted in a stationary position perpendicular to the steel strip (figure 3). Transducer outputs are recorded and measured using a digital storage oscilloscope. Temperature inside the chamber is measured using a copper-Constantan thermocouple. Static helium pressure inside the bellows is measured using a digital pressure gage connected to the bellows with a 0.15 cm i.d. tube.

TEST RESULTS

A prerequisite for testing the calibration system was the selection of one transducer as the reference to which experimental measurements and pressure calculations would be compared. Endevco model 8510-5 piezoresistive strain gage transducers, having full-scale pressure ranges of ± 34.5 kPa and full-scale outputs of 300 mV, were selected for these tests.

In order to establish a reference transducer, it was necessary to calibrate it statically over the 100-300 K temperature range and assume its static sensitivity to be equal to its dynamic sensitivity at low frequencies (< 100 Hz). The reference transducer sensitivity was measured to be 6.7 mV/kPa at 100 K and 7.0 mV/kPa at 300 K (figure 4). The test transducer was also calibrated and measured to have sensitivities of 5.9 mV/kPa at 100 K and 6.1 mV/kPa at 300 K (figure 5). Both transducers were operated at excitation voltages of 10 VDC. Between 100 K and 300 K, both transducers exhibited thermal sensitivity shifts of less than 0.07%/K, and thermal zero shifts of less than 0.02% FSO/K. Figure 6 illustrates the thermal zero shifts for the transducers.

Next the proximity probe was calibrated to accurately measure the shaker drive rod displacement. The proximity probe was calibrated over a 0.25-cm range (fig. 7). The bellows volume was calculated from manufacturer design specifications to be 0.36 cm³ in its unextended position. Given the initial transducer-bellows assembly volume, and measuring the bellows displacement and the static pressure inside the bellows, the dynamic pressure produced by the bellows motions was calculated. Displacement was measured using the proximity probe apparatus. The bellows static pressure was generally held constant at a differential pressure of 6.9 kPa (1.0 psi), but an increase in bellows static pressure was sometimes used to produce an increased dynamic pressure. Helium was used to purge the system and control static pressure in order to eliminate moisture condensation and gas liquefaction at cryogenic temperature. Temperature was measured with a copper-Constantan thermocouple mounted inside the bellows. Experiments were performed at 100, 150, 200, 250, and 300 K over a frequency range of 40 to 100 Hz to determine operational characteristics such as dynamic pressure produced, changes in gas temperature, and bellows displacement.

The change in dynamic pressure amplitude as a function of frequency was measured over a frequency range of 40 to 100 Hz. The highest peak-to-peak dynamic pressure generated was approximately 1.4 kPa (0.2 psi) for a bellows static pressure of 6.1 kPa (0.9 psid). Figure 8 illustrates the quality of the sinusoidal curve at 100 Hz, showing a clean single frequency pressure signal. Dynamic pressure was highest near the shaker's loaded resonant frequency of approximately 60 Hz.

The effect of bellows oscillation on gas temperature was measured by oscillating the bellows for 20 minutes while immersed in a 150 \pm 1 K environment. With the \pm 1 K temperature resolution, no measurable change in bellows gas temperature was measured.

Using the proximity probe calibration data, drive rod displacement was measured as a function of frequency for the 40-100 Hz range over a temperature range of 100 to 300 K. The transducers were removed in order to unseal the bellows assembly volume, thus venting the system to atmospheric pressure and eliminating static pressure loading. Maximum displacement occurred at approximately 50 Hz, as figure 9 illustrates. Chamber environmental temperature was found to have no appreciable effect on the displacement-frequency curve, but it was found that an increase in bellows static pressure caused an increase in system resonant frequency and a slight change in the shape of the curve by essentially increasing the spring constant of the system.

Finally, a test was done to compare measured and calculated dynamic pressures at cryogenic temperature. The bellows was oscillated from 40-100 Hz at 100 K. Assuming the reference transducer's static and dynamic sensitivities to be equal at low frequencies, the sinusoidal pressure amplitude was measured and compared to the pressure calculated using equation (5). The resonant frequency of the loaded system was approximately 60 Hz. This comparison is illustrated in figure 10 (ambient temperature) and figure 11 (cryogenic temperature). Curves for measured and calculated pressure as a function of frequency agree favorably with a maximum difference of approximately 11% at 40 and 80 Hz.

ERROR ANALYSIS

Given the bellows displacement (L), volume (V), cross-sectional area (A), and static pressure (P), peak-to-peak dynamic pressure (P_{p-p}) was determined by equation (5).

The uncertainty of the digital pressure gage used to measure the static pressure was 0.25% of reading. According to calculations from manufacturer tolerances, the uncertainties in the bellows volume and cross-sectional area were each determined to be approximately 5%. Based on tests for repeatability, the uncertainty in displacement was also determined to be approximately 5%. Equation (5) was differentiated to find $\partial P_{p-p} / \partial L$, $\partial P_{p-p} / \partial V$, $\partial P_{p-p} / \partial A$, and $\partial P_{p-p} / \partial P$. The overall uncertainty in dynamic pressure measurement was found to be approximately 11% RMS.

CONCLUDING REMARKS

The cryogenic dynamic pressure calibration system has the capability of producing dynamic pressure of 1.4 kPa (0.2 psi) at frequencies of 40-100 Hz from ambient to cryogenic temperatures. The system can also be used to perform static calibrations over the same temperature range at pressures up to 70 kPa (10 psi). Dynamic pressure amplitudes developed are determined to within an uncertainty of 11%. The most significant sources of error are the uncertainties in displacement measurement, and in bellows volume and cross-sectional area. Overall system measurement uncertainty can be most easily reduced by the improvement in the displacement measurement technique, since uncertainties in bellows volume and cross-sectional area are largely dependent upon manufacturer's tolerances. System measurement uncertainty will be greatly improved by replacing the proximity probe displacement measurement apparatus and shaker with a system capable of servo-controlling and measuring the bellows oscillation frequency and displacement. Thermal contraction can also be controlled by building the oscillating bellows apparatus frame and drive rod from Invar steel, an alloy with a small coefficient of thermal contraction at cryogenic temperature. The design of an operational system having components and materials specifically selected will improve the overall system performance to provide high quality data.

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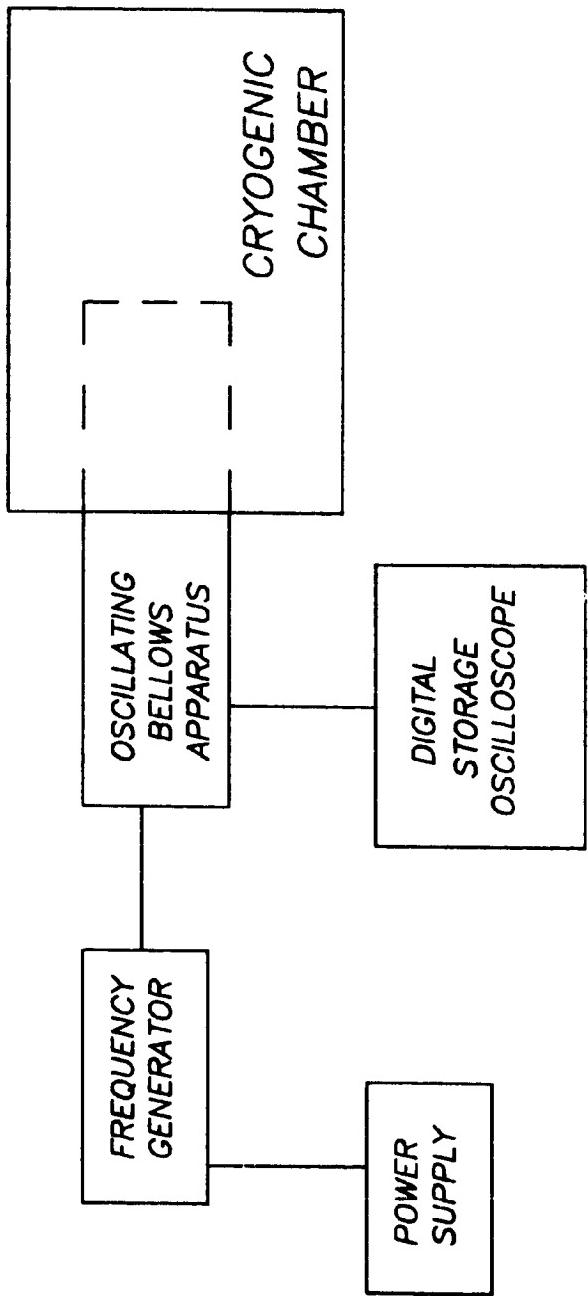


FIGURE 1 - CALIBRATION SYSTEM APPARATUS

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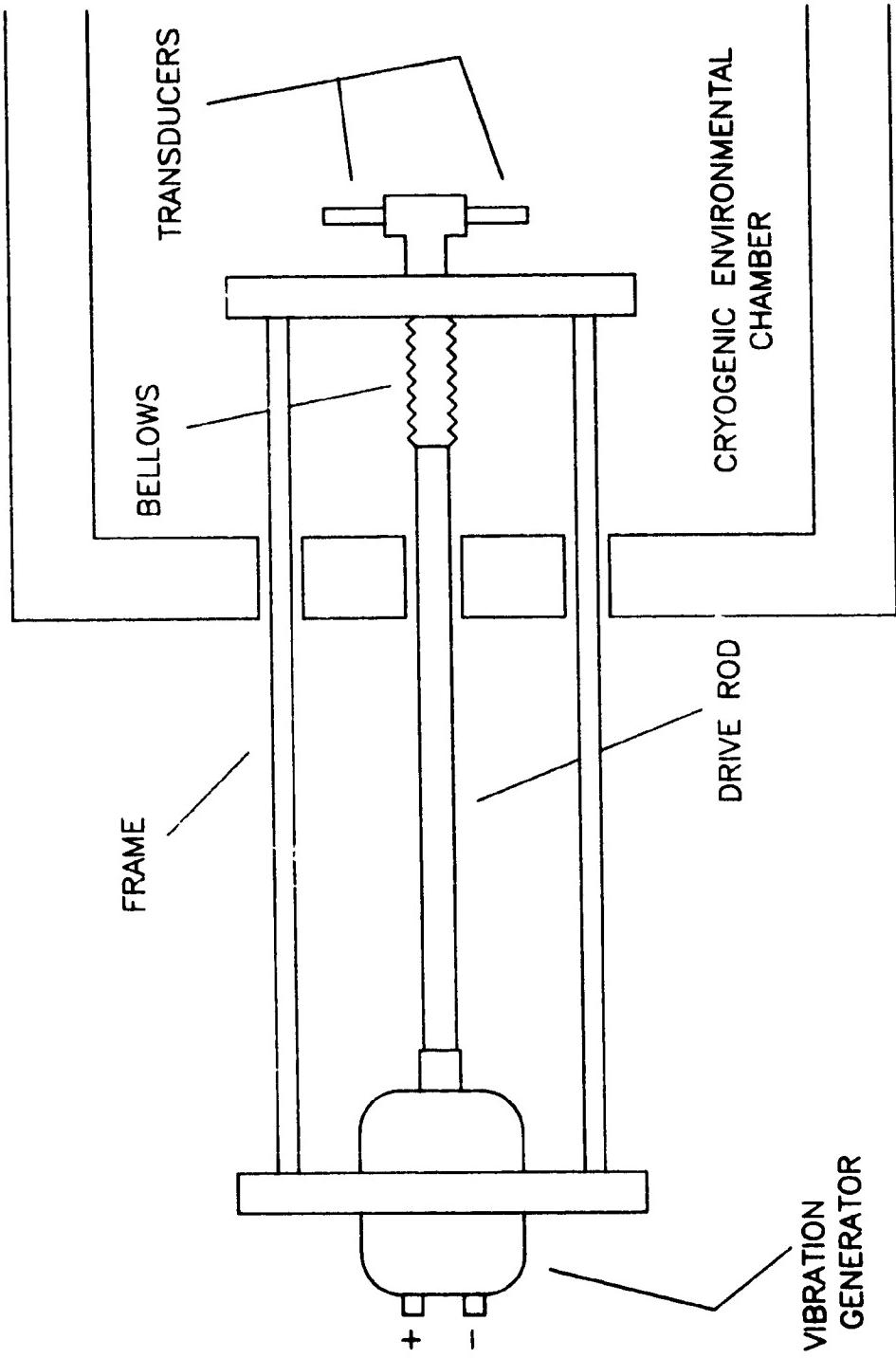


FIGURE 2-OSCILLATING BELLOWS APPARATUS

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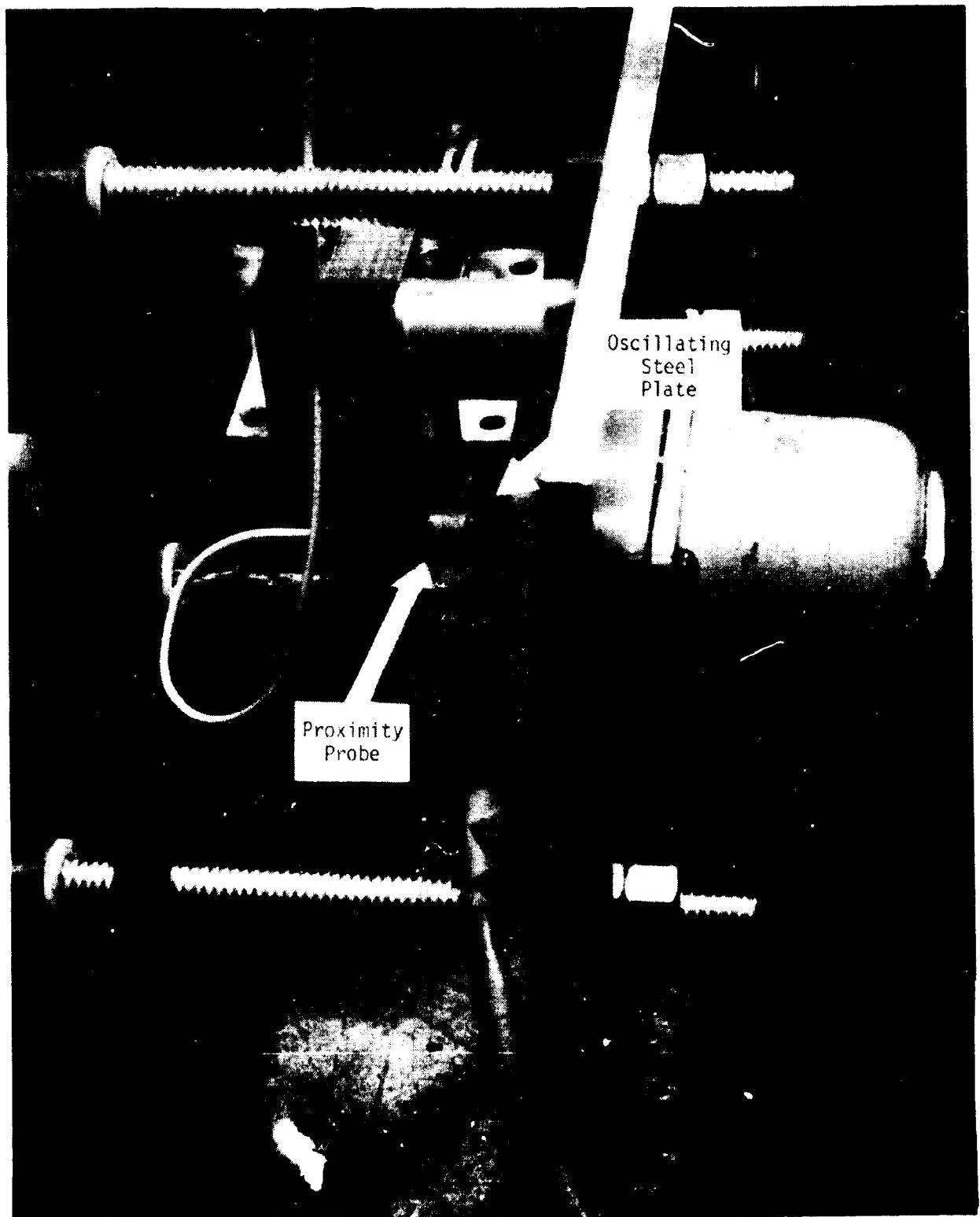


FIGURE 3-PROXIMITY PROBE APPARATUS

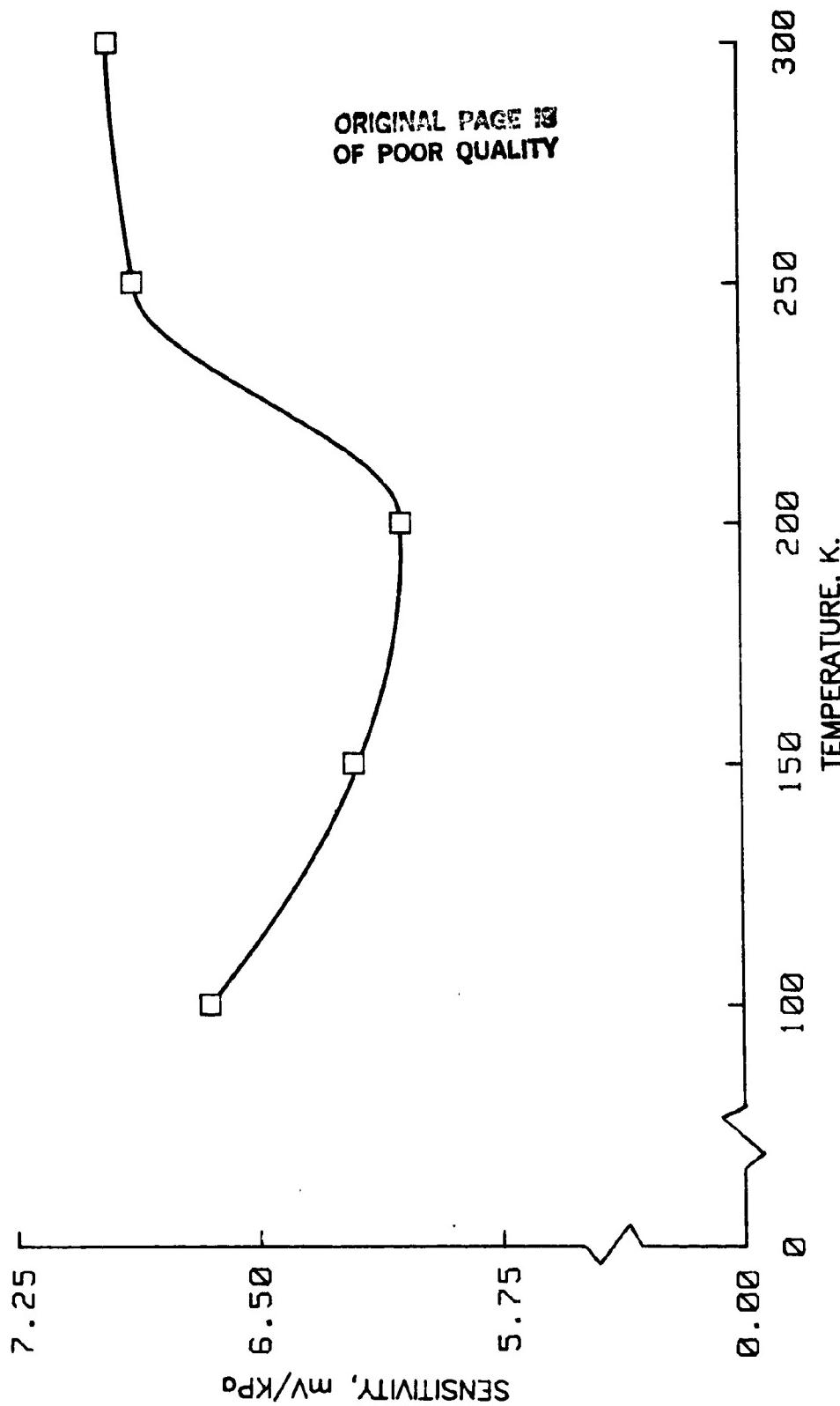


FIGURE 4—REFERENCE TRANSDUCER
SENSITIVITY AS A FUNCTION
OF TEMPERATURE

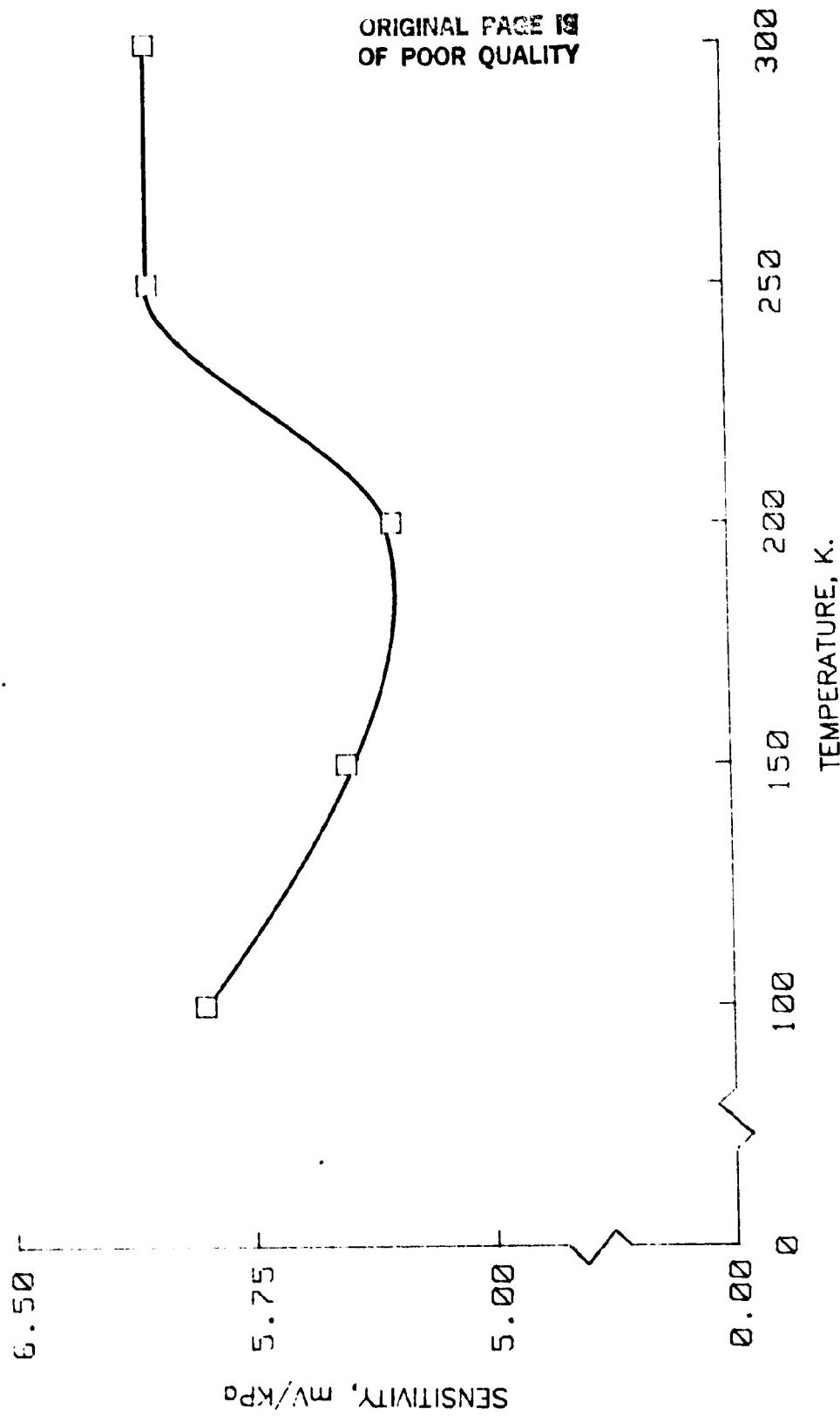


FIGURE 5—TEST TRANSDUCER SENSITIVITY
AS A FUNCTION OF TEMPERATURE

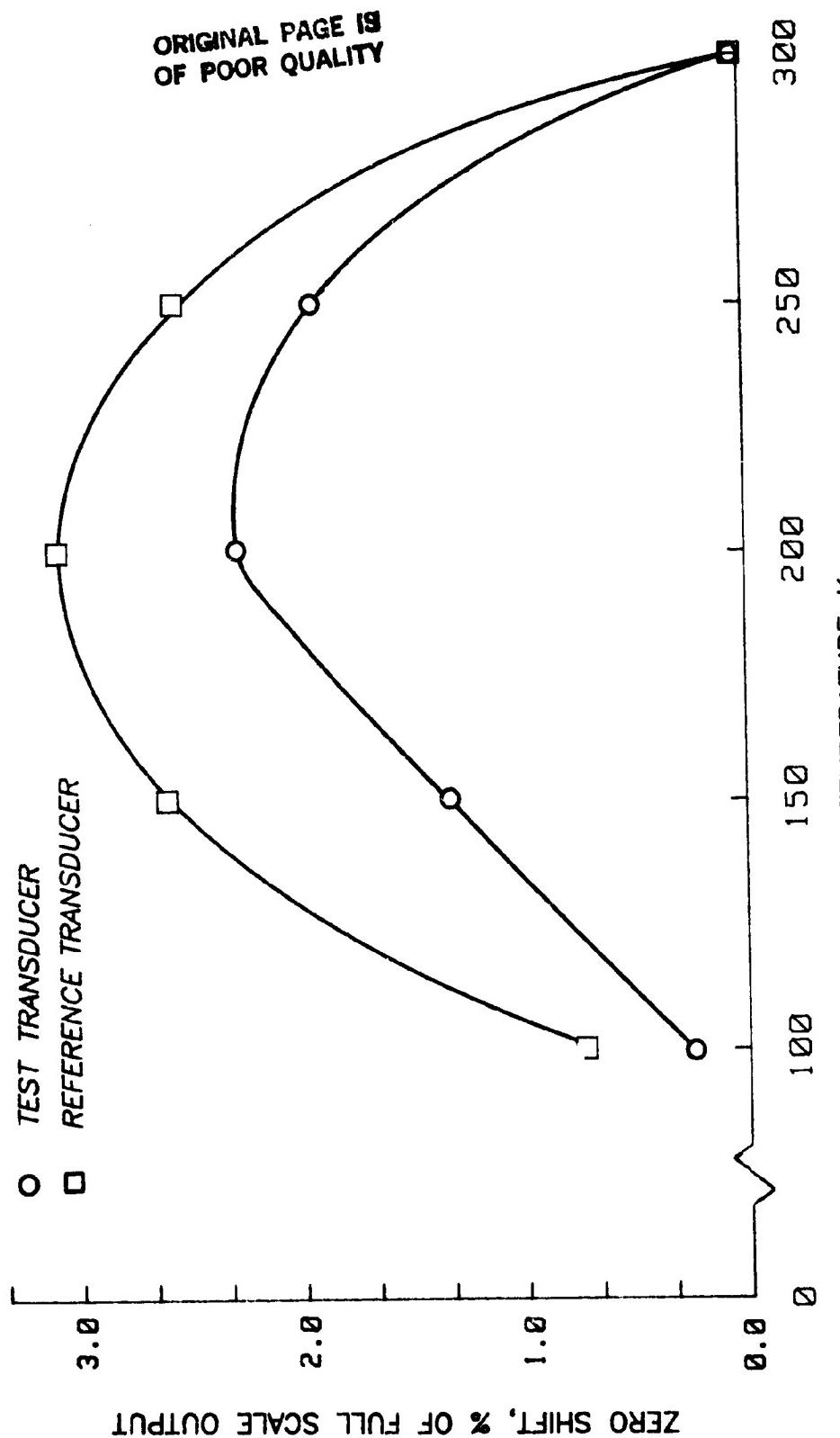


FIGURE 6-ZERO SHIFT AS A FUNCTION
OF TEMPERATURE

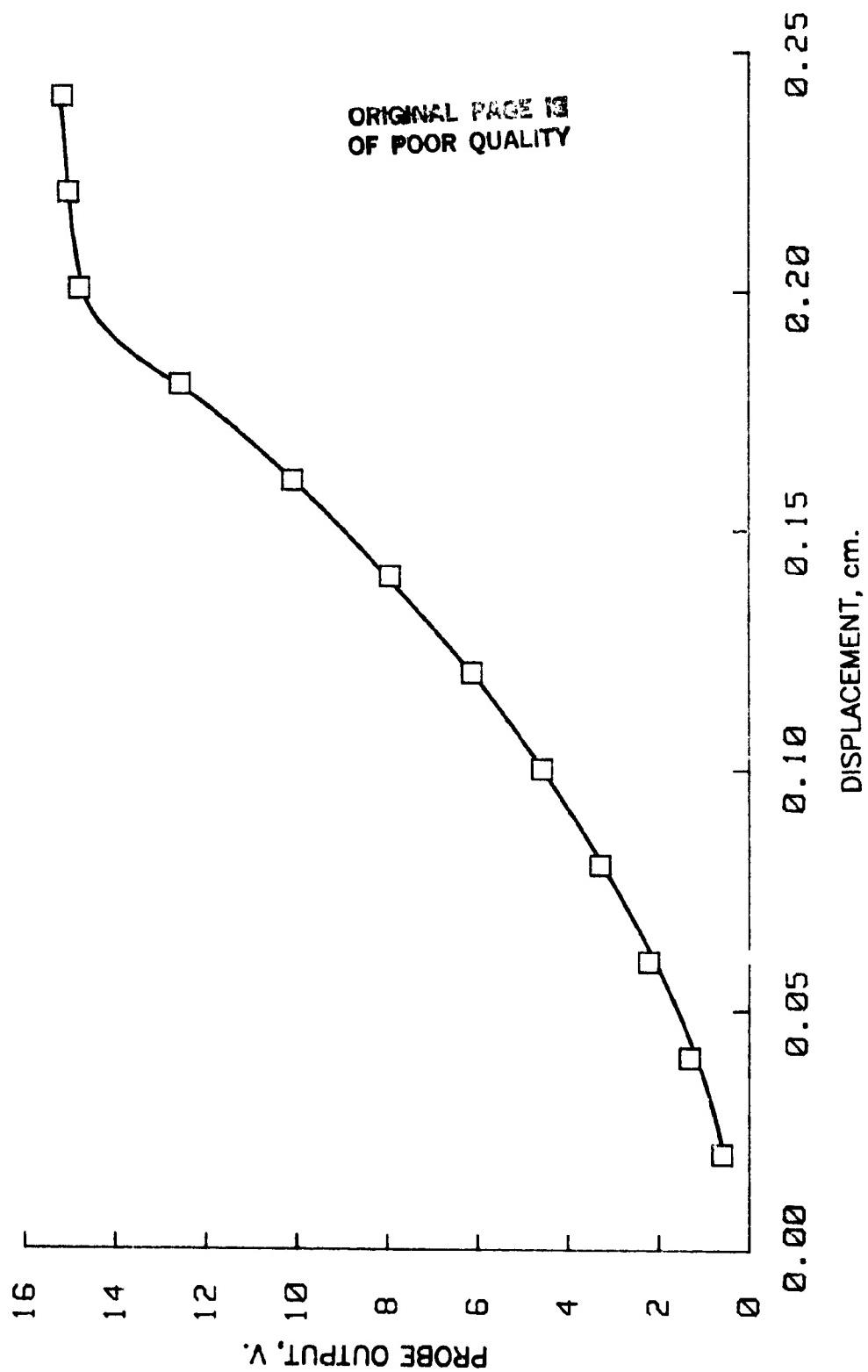
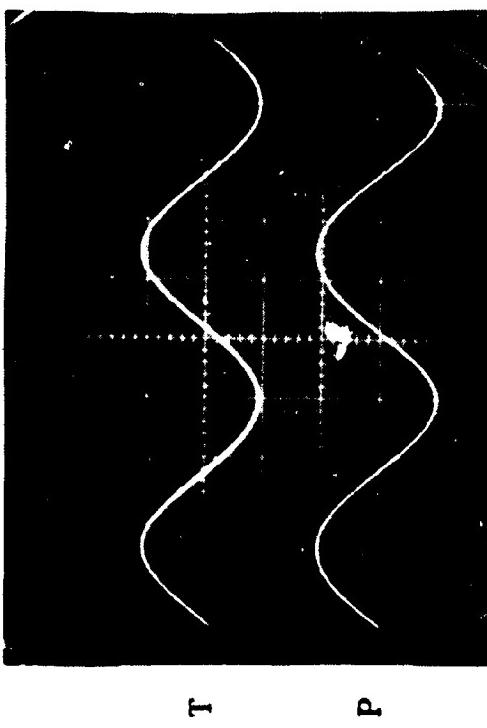
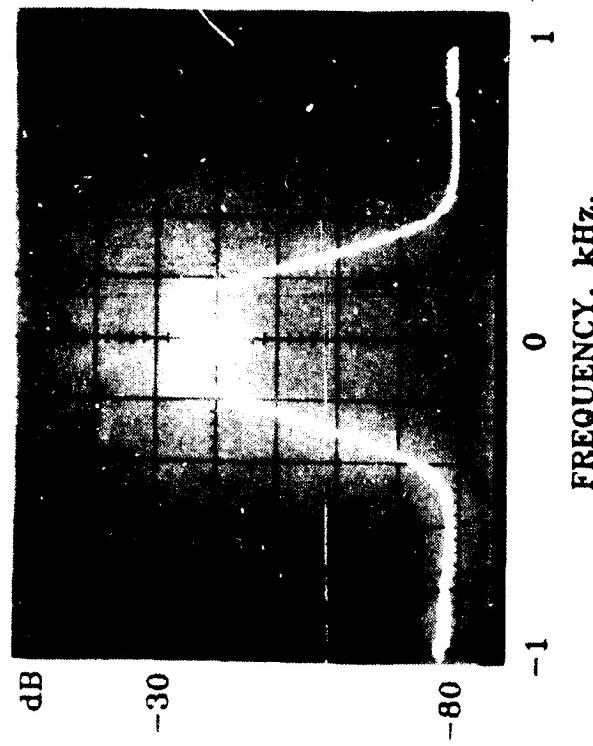


FIGURE 7-PROXIMITY PROBE CALIBRATION

TRANSDUCER/PROBE SIGNALS



TRANSDUCER FREQUENCY SPECTRUM



TIME 2 mS/DIV.
T-0.5mV/DIV.
P-500mV/DIV.

Peak-to-Peak Pressure = 1.7 KPa

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FIGURE 8 - SINUSOIDAL PRESSURE CURVES
AT 100 Hz. AND 100 K.

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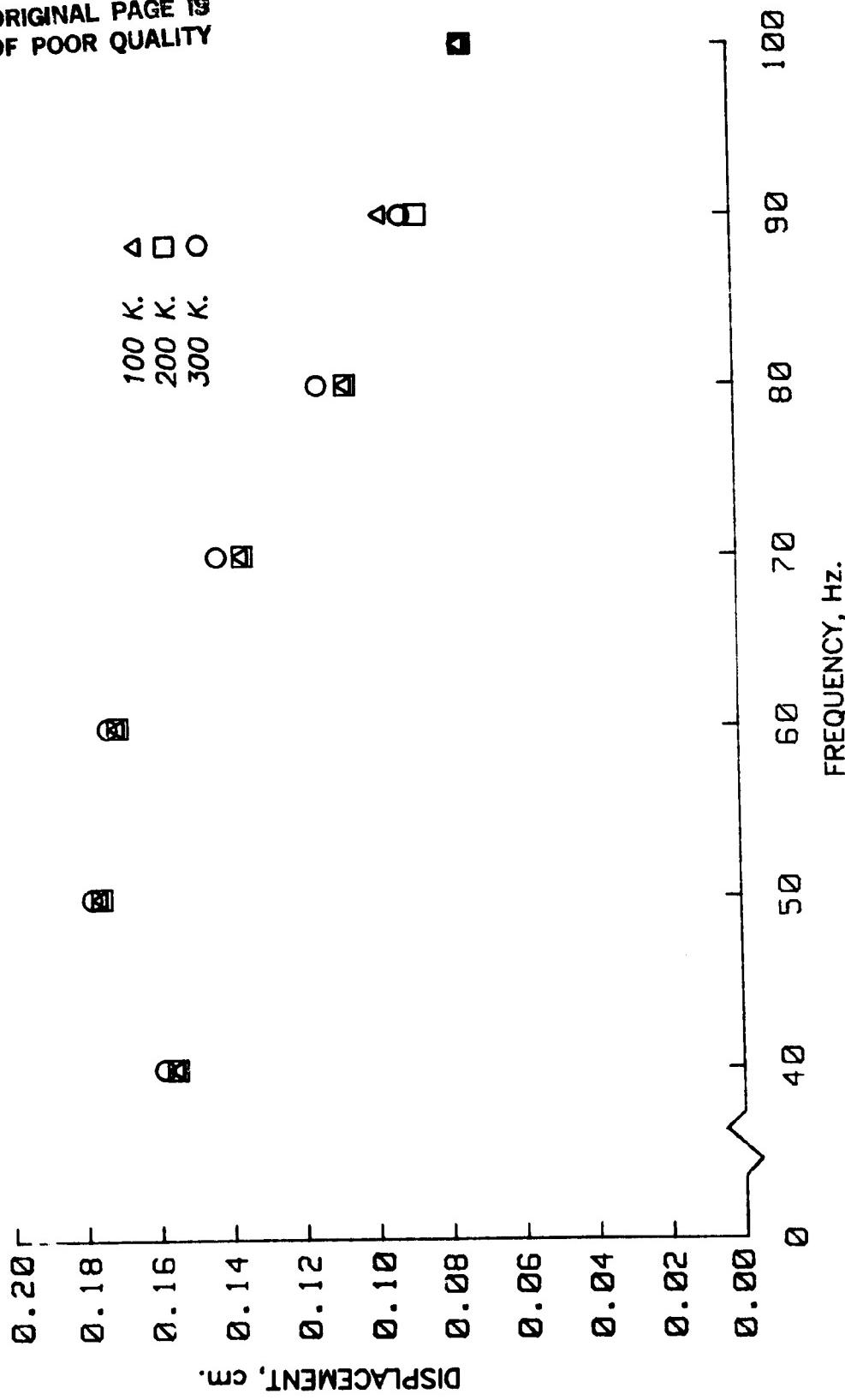


FIGURE 9 - BELLOWS DISPLACEMENT AS A
FUNCTION OF FREQUENCY

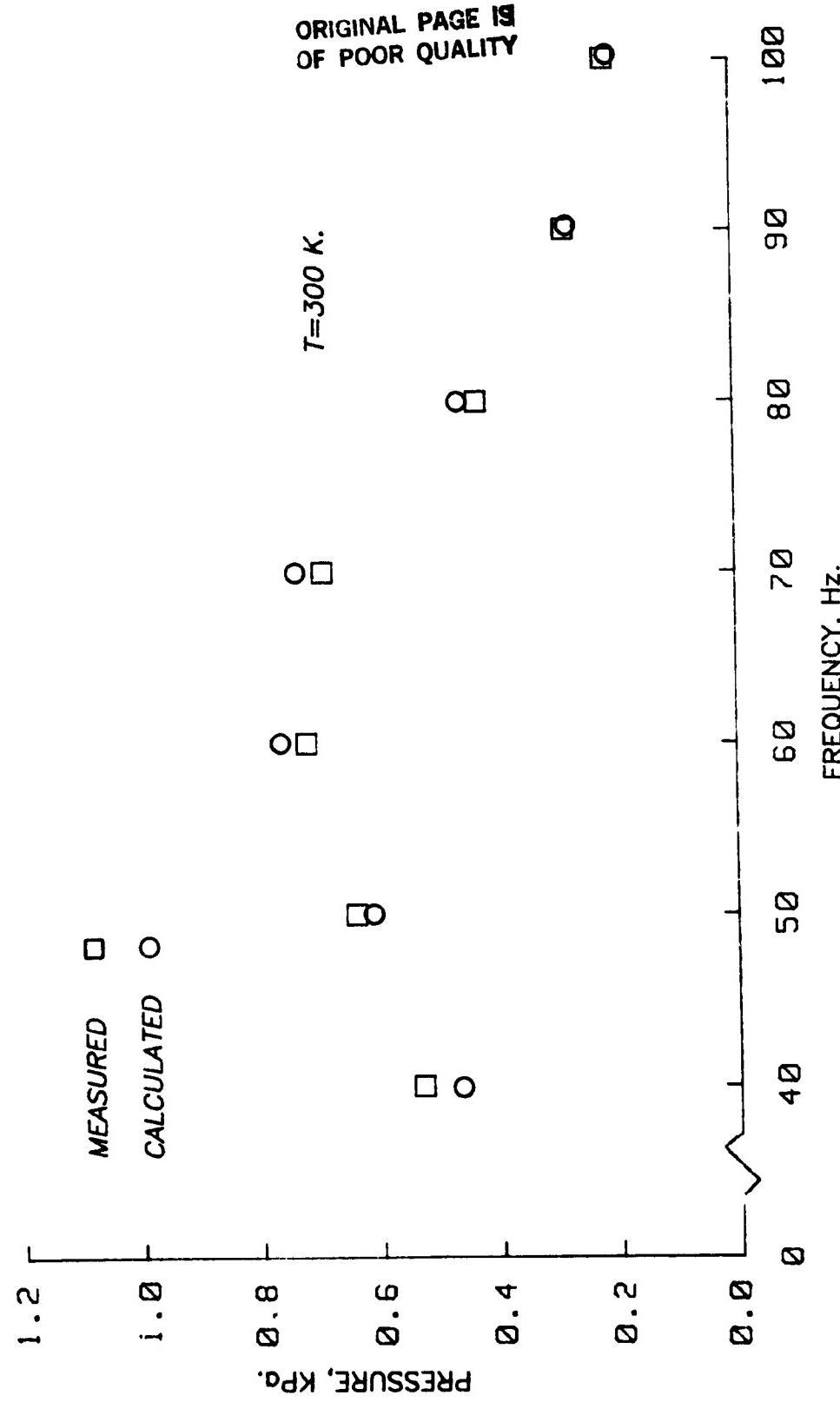


FIGURE 10 - MEASURED AND CALCULATED
PRESSURES AS A FUNCTION OF FREQUENCY

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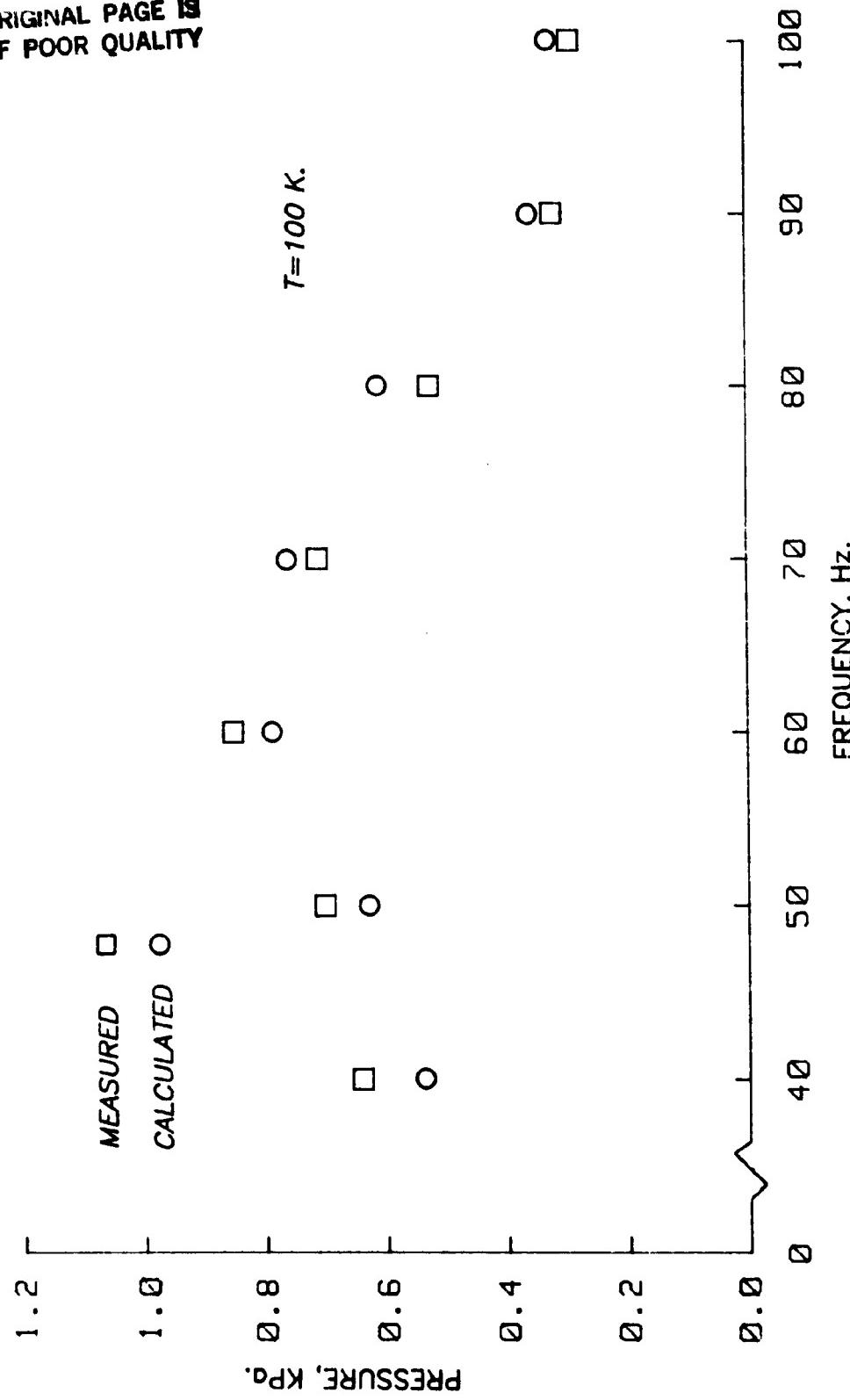


FIGURE 11-MEASURED AND CALCULATED
PRESSURES AS A FUNCTION OF FREQUENCY